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Chapter 25

SINGLE-PHASE IM TRANSIENTS

25.1 INTRODUCTION

Single-phase induction motors undergo transients during starting, load perturbation or voltage sags etc. When inverter fed, in variable speed drives, transients occur even for mechanical steady state during commutation mode.

To investigate the transients, for orthogonal stator windings, the cross field (or d-q) model in stator coordinates is traditionally used. [1]

In the absence of magnetic saturation, the motor parameters are constant. Skin effect may be considered through a fictitious double cage on the rotor.

The presence of magnetic saturation may be included in the d-q model through saturation curves and flux linkages as variables. Even for sinusoidal input voltage, the currents may not be sinusoidal. The d-q model is capable of handling it. The magnetisation curves may be obtained either through special flux decay standstill tests in the d-q (m.a) axes (one at a time) or from FEM-in d.c. with zero rotor currents. The same d-q model can handle nonsinusoidal input voltages such as those produced by a static power converter or by power grid polluted with harmonics by other loads nearby.

To deal with nonorthogonal windings on stator, a simplified equivalence with a d-q (orthogonal) winding system is worked out. Alternatively a multiple reference system + - model is used [3]

While the d - q model uses stator coordinates, which means a.c. during steady state, the multiple-reference model uses + - synchronous reference systems which imply d.c. steady state quantities. Consequently, for the investigation of stability, the frequency approach is typical to the d-q model while small deviation linearization approach may be applied with the multiple-reference + - model.

Finally, to consider the number of stator and rotor slots-that is space flux harmonics-the winding function approach is preferred. [4] This way the torque/speed deep around 33% of no load ideal speed, the effect of the relative numbers of stator and rotor slots, broken bars, rotor skewing may be considered. Still saturation remains a problem as superposition is used.

A complete theory of single phase IM, valid both for steady-state and transients, may be approached only by a coupled FEM-circuit model, yet to be developed in an elegant computation time competitive software. In what follows, we will illustrate the above methods in some detail.

25.2 THE d-q MODEL PERFORMANCE IN STATOR COORDINATES

As in general the two windings are orthogonal but not identical, only stator coordinates may be used directly in the d-q (cross field) model of the single phase IMs.

True, when one phase is open any coordinates will do it but this is only the case of the split-phase IM after starting. [5]

First, all the d-q model variables are reduced to the main winding

$$\begin{aligned} V_{ds} &= V_s(t) \\ V_{qs} &= (V_s(t) - V_c(t))/a \\ I_{ds} &= I_m \\ I_{qs} &= I_a \cdot a \end{aligned} \quad (25.1)$$

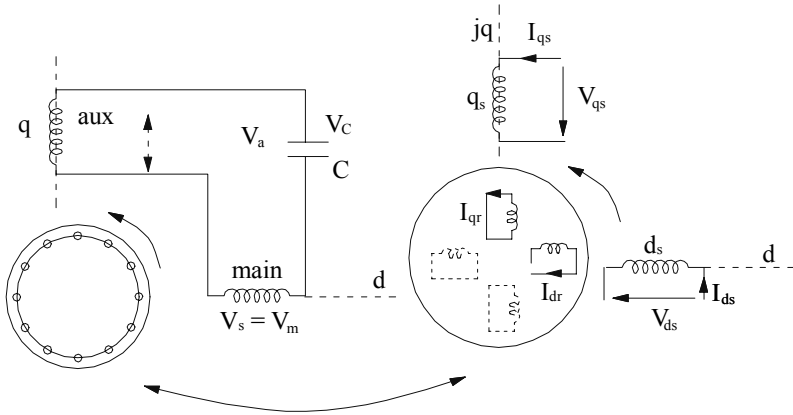


Figure 25.1 The d-q model

Where a is the equivalent turns ratio of the auxiliary to main winding.
Also

$$\frac{dV_c}{dt} = \frac{1}{C} \frac{I_{qs}}{a} \quad (25.2)$$

The d-q model equations, in stator coordinates, are now straightforward

$$\begin{aligned}
\frac{d\Psi_{ds}}{dt} &= V_s(t) - R_{sm} I_{ds} \\
\frac{d\Psi_{qs}}{dt} &= (V_s(t) - V_c(t)) / a - \frac{R_{sa}}{a^2} I_{qs} \\
\frac{d\Psi_{dr}}{dt} &= I_{dr} R_{rm} - \omega_r \Psi_{qr} \\
\frac{d\Psi_{qr}}{dt} &= I_{qr} R_{rm} + \omega_r \Psi_{dr}
\end{aligned} \tag{25.3}$$

The flux/current relationships are

$$\begin{aligned}
\Psi_{ds} &= L_{sm} I_{ds} + \Psi_{dm}; \Psi_{dm} = L_m (I_{ds} + I_{dr}) = L_m I_{dm} \\
\Psi_{dr} &= L_{rm} I_{dr} + \Psi_{dm} \\
\Psi_{qs} &= \frac{L_{sa}}{a^2} I_{qs} + \Psi_{qm}; \Psi_{qm} = L_m (I_{qs} + I_{qr}) = L_m I_{qm} \\
\Psi_{qr} &= L_{rm} I_{qr} + \Psi_{qm}
\end{aligned} \tag{25.4}$$

The magnetization inductance L_m depends both on I_{dm} and I_{qm} when saturation is accounted for because of cross-coupling saturation effects. As the magnetic circuit looks nonisotropic even with slotting neglected, the total flux vector Ψ_m is a function of total magnetization current I_m :

$$\begin{aligned}
\Psi_m &= L_m(I_m) \cdot I_m \\
I_m &= \sqrt{I_{dm}^2 + I_{qm}^2}; \Psi_m = \sqrt{\Psi_{dm}^2 + \Psi_{qm}^2}
\end{aligned} \tag{25.5}$$

Once $L_m(I_m)$ is known, it may be used in the computation process with its previous computation step value, provided the sampling time is small enough.

We have to add the motion equation

$$\begin{aligned}
\frac{J}{p_1} \frac{d\omega_r}{dt} &= T_e - T_{load}(\theta_r, \omega_r) \\
\frac{d\theta_r}{dt} &= \omega_r / p_1 \\
T_e &= (\Psi_{ds} I_{qs} - \Psi_{qs} I_{ds}) p_1
\end{aligned} \tag{25.6}$$

Equations (25.2)-(25.6) constitute a nonlinear 7th order system with V_c , I_{ds} , I_{qs} , I_{dr} , I_{qr} and ω_r , θ_r as variables. The inputs are $V_s(t)$ -the source voltage and T_{load} -the load torque.

The load torque may vary with speed (for pumps, fans) or with rotor position (for compressors).

In most applications, θ_r does not intervene as the load torque depends on speed, so the order of the system becomes six.

When the two stator windings do not occupy the same number of slots, there may be slight differences between the magnetization curves along the two

axes, but they are in many cases small enough to be neglected in the treatment of transients.

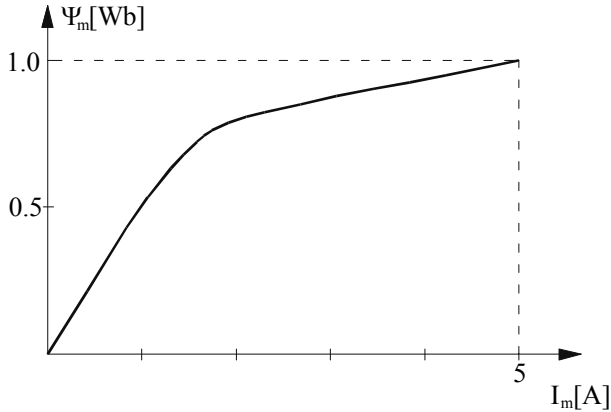


Figure 25.2 The magnetization curve

A good approximation of the magnetization curve may be obtained through FEM, at zero speed, with d.c. excitation along one axis and contribution from the second axis. Dc current decay tests at standstill in one axis, with dc current injection in the second axis should provide similar results. After many “points” in [Figure 25.2](#) are calculated, curve fitting may be used to yield a univoque correspondance between Ψ_m and I_m .

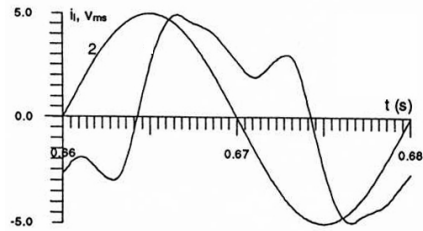
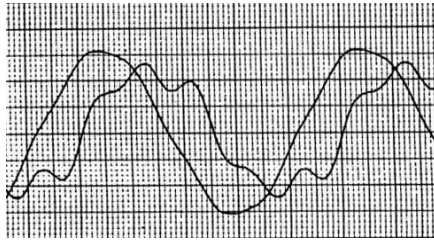
As expected, if enough digital simulation time for transients is allowed, steady state behaviour may be reached.

In the absence of saturation, for sinusoidal power source voltage, the line current is sinusoidal for no-load and under load.

In contrast, when magnetic saturation is considered, the simulation results show nonsinusoidal line current under no-load and load conditions ([Figure 25.3](#)). [2]

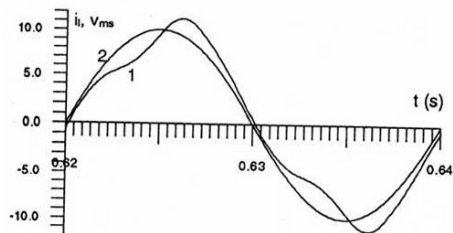
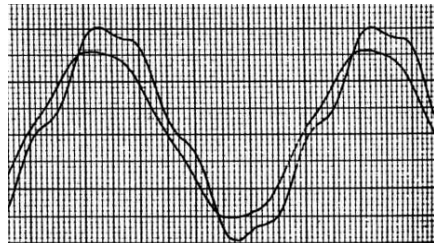
The influence of saturation is visible. It is even more visible in the main winding current RMS computation versus experiments. ([Figure 25.4](#)) [2]

The differences are smaller in the auxiliary winding for the case in point: $P_n = 1.1$ kW, $U_n = 220$ V, $I_n = 6.8$ A, $C = 25$ μ F, $f_n = 50$ Hz, $a = 1.52$, $R_{sm} = 2.6$ Ω , $R_{sa} = 6.4$ Ω , $R_{rm} = 3.11$ Ω , $L_{sm} = L_{rm} = 7.5$ mH, $J = 1.1 \times 10^{-3}$ Kg m^2 , $L_{sa} = 17.3$ mH. The magnetization curve is as in [Figure 25.2](#). The motor power factor, calculated for the fundamental, at low loads, is much less than predicted by the nonsaturated d-q model. On the other hand it looks like the saturated d-q model produces results which are very close to the experimental ones, for a wide range of loads.



a.)

b.)



c.)

d.)

Figure 25.3 Steady state by the d-q model with saturation included

a.) and b.)-no load

c.) and d.)-on load

a.) and c.)-test results

b.) and d.)-digital simulation

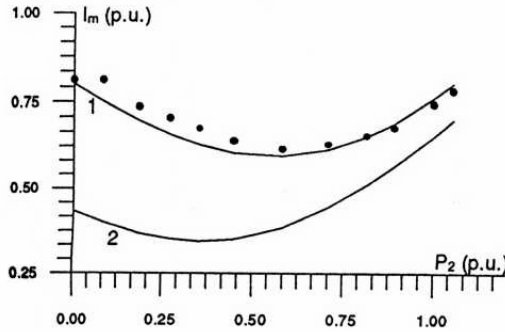


Figure 25.4. RMS of main winding current versus output power
1-saturated model
2-unsaturated model
•-test results

This may be due to the fact that the saturation curve has been obtained through tests and thus the saturation level is tracked for each instantaneous value of magnetization current (flux).

The RMS current correct prediction by the saturated d-q model for steady state represents notable progress in assessing more correctly the losses in the machine.

Still, the core losses-fundamental and additional-and additional losses in the rotor cage (including the interbar currents) are not yet included in the model. Space harmonics though apparently somehow included in the $\Psi_m(I_m)$ curve are not thoroughly treated in the saturated d-q model.

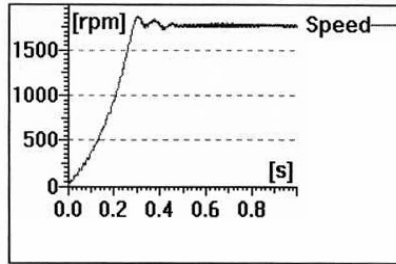
25.3 STARTING TRANSIENTS

It is a known fact that during severe starting transients, the main flux path saturation does not play a crucial role. However it is there embedded in the model and may be used if so desired.

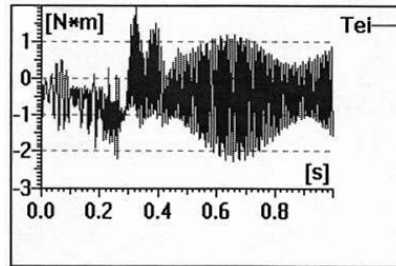
For a single phase IM with the data: $V_s = 220$ V, $f_{1n} = 50$ Hz, $R_{sm} = R_{sa} = 1$ Ω , $a = 1$, $L_m = 1.9$ H, $L_{sm} = L_{sa} = 0.2$ H, $R_{rm} = 35$ Ω , $L_{rm} = 0.1$ H, $J = 10^{-3}$ Kg m^2 , $C_a = 5$ μ F, $\zeta = 90^\circ$, the starting transients are presented on [Figure 25.5](#). The load torque is zero from start to $t = 0.4$ s, when a 0.4 Nm load torque is suddenly applied.

The average torque looks negative because of the choice of signs.

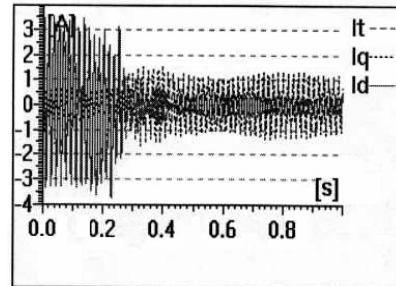
The torque pulsations are large and so evident on [Figure 25.5 b](#)), while the average torque is 0.4 Nm, equal to the load torque. The large torque pulsations reflect the departure from symmetry conditions. The capacitor voltage goes up to a peak value of 600 V, another sign that a larger capacitor might be needed.



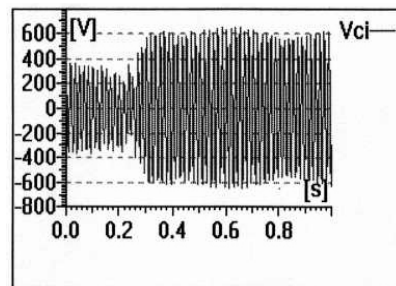
a.)



b.)



c.)



d.)

Figure 25.5 Starting transients
a.) speed versus time, b.) torque versus time
c.) input current versus time, d.) capacitor voltage versus time

The hodograph of stator current vector

$$I_s = I_d + jI_q \quad (25.7)$$

is shown on Figure 25.6.

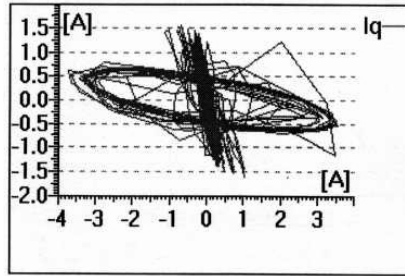
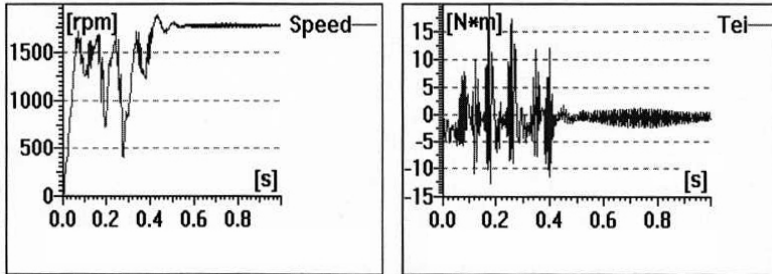


Figure 25.6 Current hodograph during starting

For symmetry, the current hodograph should be a circle. Not so in Figure 25.6.

To investigate the influence of capacitance on the starting process, the starting capacitor is $C_s = 30\mu\text{F}$, and then at $t = 0.4\text{s}$ the capacitance is reduced suddenly $C_a = 5\mu\text{F}$ (Figure 25.7)



a.)

b.)

Figure 25.7 Starting transients for $C_s = 30\mu\text{F}$ at start and $C_a = 5\mu\text{F}$ from $t = 0.4\text{s}$ on
a.) speed; b.) torque

The torque and current transients are too large with $C_s = 30\mu\text{F}$, a sign that the capacitor is now too large.

25.4 THE MULTIPLE REFERENCE MODEL FOR TRANSIENTS

The d-q model has to use stator coordinates as long as the two windings are not identical. However if the d-q model is applied separately for the instantaneous + and-(f, b) components then for synchronous coordinates: $+\omega_1$ (for the +(f) component) and $-\omega_1$ (for the - (b) component), the steady state means d.c. variables. [3]

Consequently, the dynamic (stability) analysis may be performed via the system linearization (small deviation theory).

Stability to sinusoidal torque pulsation such as in compressor loads, can thus be treated. The superposition principle precludes the inclusion of magnetic saturation in the model. [3]

25.5 INCLUDING THE SPACE HARMONICS

The existence of space harmonics causes torque pulsations, cogging, and crawling.

The space harmonics have three origins, as mentioned before in Chapter 23,

- Stator m.m.f. space harmonics
- Slot opening permeance pulsations
- Main flux path saturation

A general method to deal with space harmonics of all these three origins is presented in Reference 6 based on the multiple magnetic circuit approach. The rotor is considered bar by bar.

Reference 4 treats space harmonics produced only by the stator m.m.f. but deals also with the effect of skewing. Based on the winding function approach, the latter method also considers m windings in the stator and N_r bars in the rotor. Magnetic saturation is neglected.

The deep(s) in the torque/speed curve may be predicted by this procedure. Also the influence of the ratio of slot numbers N_s/N_r of stator and rotor and of cogging (parasitic, asynchronous) torques is clearly evidentiated. As an example, Figure 25.8 illustrates [4] the starting transients of a single-phase capacitor motor with the same number of slots per stator and rotor, without skewing. As expected, the motor is not able to start due to the strong parasitic synchronous torque at stall (Figure 25.8 a)

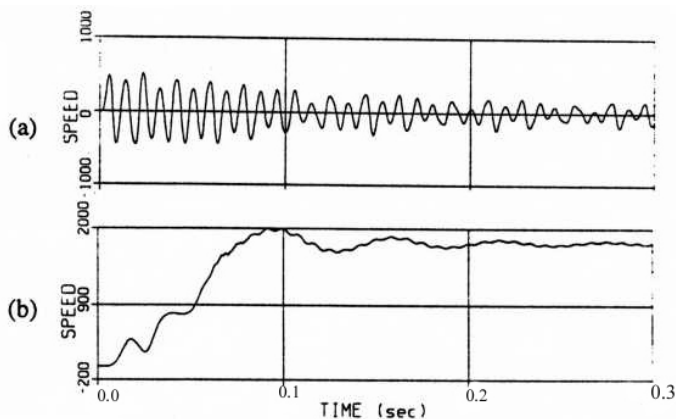


Figure 25.8 Starting speed transients for $N_s = N_r$
a) without skewing b) with skewing

With skewing of one slot pitch, even with $N_s = N_r$ slots, the motor can start (Figure 25.8 b).

25.6 SUMMARY

- Transients occur during starting or load torque perturbation operation modes.
- Also power source voltage (and frequency) variation cause transients in the single phase IM.
- When power converter (variable voltage, variable frequency)-fed, the single phase IM experiences time harmonics also.
- The standard way to handle the single phase IM is by the cross-field (d-q) model when magnetic saturation, time harmonics and skin effect may be considered simultaneously.
- Due to magnetic saturation the main winding and total stator currents depart from sinusoidal waveforms, both at no-load and under load conditions. The magnetic saturation level depends on load, machine parameters and on the capacitance value. It seems that neglecting saturation leads to notable discrepancy between the main and total currents measured and calculated RMS values. This is one of the reasons why losses are not predicted correctly, especially for low powers.
- Switching the starting capacitor off produces important speed, current, and torque transients.
- The d-q model has a straightforward numerical solution for transients but, due to the stator winding asymmetry, it has to make use of stator coordinates to yield rotor position independent inductances. Steady state means a.c. variables at power source frequency. Consequently, small deviation theory, to study stability, may not be used, except for the case when the auxiliary winding is open.
- The multiple reference system theory, making use of + - (f,b) models in their synchronous coordinates ($+\omega_1$ and $-\omega_1$) may be used to investigate stability after linearization.
- Finally, besides FEM-circuit coupled model, the winding function approach or the multiple equivalent magnetic circuit method simulate each rotor bar and thus asynchronous and synchronous parasitic torques may be detected.
- A FEM-circuit couple model (software), easy to handle, and computation time competitive, for single-phase IM, is apparently not available as of this writing.

25.7 REFERENCES

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